An Integrated Near-Infrared Camera for NGST

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ABSTRACT

We present a design of an 8192×8192 pixel format near-infrared camera operating from 0.6–5.3 μm with optics which will accommodate both direct imaging and spectroscopic functions. **Focal plane sharing is the most cost-effective way to maximize the number of pixels available for both imaging and spectroscopy.** The detector modules consist of four separate 4096×4096 pixel mosaics of focal plane arrays, each fed by a 1:1 Offner relay located after a pyramid beam separator which splits the incident light into four separate paths. Fixed wide-band (50–100% passband) and moderate-band (5–20% passband) filters and **tunable narrow band filters** (<1% passband) are mounted near the pupils in the Offners where the light bundles have their minimum diameters. **Three plate scales are provided**; a wide-field f/12 mode with an $8' \times 8'$ field of view providing critical sampling at 4 μm, an f/24 $4' \times 4'$ field of view providing critical sampling at 2 μm, and a high-resolution f/64 mode using one quadrant to provide a $41'' \times 41''$ field of view with critical sampling at 0.75 μm. Two-position binary mechanisms placed between the Offner relays and the detector packages introduce focal reducers or focal extenders to provide the wide-field (f/12) and high-resolution (f/64) imaging modes. Either one of the science detectors or a small-area off-center detector is used to control the fast steering mirror. Focal plane sharing between imaging and spectrographic modes will also be achieved with binary mechanisms which introduce beam extraction/injection mirrors into the optical path. The camera moving parts count consists of two sets of filter wheels, a binary mechanism to switch-in the MOS, eight small binary mechanisms placed after the Offner relays, and shutters. Either broad-band HgCdTe or InSb devices in either 1024×1024 or 2048×2048 formats can be used with this design. However, InSb is preferred because the 25 μm pixel pitch minimizes OTA aberrations and InSb has superior QE performance near the short wavelength cut-off.

1. Science

1.1. Executive Summary

We propose to deploy an 8192×8192 pixel focal plane mosaic which is used for both imaging and spectroscopy in the 0.6–5.3 μm wavelength range. The camera will utilize a set of broad-band and moderate-band fixed filters, narrow-band tunable filters, and provide three distinct image scales with fields of view as large as $8' \times 8'$ and critical sampling at 0.75, 2, and 4μm. Simple mechanisms are used to enable the same focal plane array to serve both imaging and spectroscopic functions. Focal plane sharing permits the deployment of the maximum number of pixels for each application, thereby maximizing the science return and the speed with which the Design Reference Mission (DRM) can be executed, while limiting the total number of flight detectors needed to be fabricated, tested, packaged, and integrated.

The direct imaging modes are optimized for background-limited performance (by zodiacal light) over the entire operating wavelength range. The proposed design maximizes the usable field of view and at the same time permits diffraction-limited performance over the entire NGST prime-band wavelength range. The optical design and filter choices are optimized for both deep extragalactic surveys and Galactic studies. This instrument is designed to take advantage of the 'cosmological window' near 3 μm where there is a minimum in the zodiacal background light. This saddle point occurs where the zodiacal emission transitions from predominantly scattered sunlight producing increasing background fluxes towards shorter wavelengths, and the thermal re-radiation by warm interplanetary grains producing increasing fluxes towards longer wavelengths.

The wide-field (f/12) mode enables imaging over an $8'$ square FOV with 60 milli arc-second pixel resolution. This mode provides for efficient detection of cosmological supernovae, the acquisition of the largest samples of galaxies possible with NGST, and will enable the investigation of the clustering properties and spatial distribution of galaxies as a function of redshift. This mode is also optimized to provide critically sampled and diffraction-limited images at the long wavelength end of the camera. This capability will permit the study of very red ultra-high redshift objects, highly dust enshrouded sources, and cool Galactic targets including young stars, proto-planetary disks, evolving post-main sequence stars, and brown dwarfs.

The moderate-field (f/24) mode enables critically sampled imaging in the 3 μm 'cosmological window' in the middle of the camera pass-band with 30 milli arc-second pixel resolution. This mode is optimized for ultra-deep cosmological imaging and the investigation of more mature and less obscured star forming regions in our Galaxy.

The high-resolution (f/64) mode enables 10 milli arc-second imaging at the shortest wavelengths observable with NGST with three times better linear resolution than the Hubble

Space Telescope. This mode is optimized for studies of proto-planetary disks in irradiated environments such as the Orion Nebula proplyds, provides the best chance to directly image giant planets around nearby stars, and is the best instrument to investigate the small-scale structure of galaxies, quasars, Galactic targets, and Solar System objects with unprecedented angular resolution. This mode provides a unique Solar System capability on NGST that can produce full-disk images of all planets, image surface features on moons and asteroids, and resolve cometary nuclei. This mode provides a direct link to the science legacy inherited from HST by providing access to the red portion of the visual wavelength range.

The fixed-band filters permit the determination of approximate redshifts and the photometric characterization of target sources. The tunable filters will permit determination of precise redshifts, the acquisition of images in a variety of spectral lines and features at arbitrary redshift or rest-wavelength. Applications include recombination and resonance line imaging at all cosmological epochs (cf. Lyman limit, Lyman α, Hα, Paschen α, and Brackett α, and metal lines) and the selective imaging of specific molecular bands and features (cf. PAHs, CO, methane, H_2). The tunable filters will provide low-resolution (R = 100) spectroscopic data-cube acquisition capability. The chemical evolution of the Universe can be mapped as a function of redshift. Ionic, atomic, molecular, and solid-state transitions in the NGST prime-band will be used to study the evolution of abundances with cosmic time.

We propose to share the focal plane with spectroscopic instruments provided by other groups. We will develop the detailed optical, mechanical, and control interface specifications in concert with the groups developing those instruments. We will also provide and integrate the mechanisms needed to direct the light processed by these instruments to our focal plane assembly. This strategy minimizes the number of required detector assemblies and cost, and maximizes the number of pixels which can be delivered for each application. Focal plane sharing with the multi-object spectrograph permits the utilization of multiple plate-scales provided by the camera, providing a very wide FOV and large numbers of pixels. By providing R=1000–2000, precise redshifts and source characteristics can be derived for both cosmological and galactic targets.

The binary mechanisms identical to those used to change the f/ratio will also be made available to extract the beam after the Offner optics, process the light through any of several spectroscopic entrance apertures, disperse the transmitted light, and re-image the light onto the detector assembly. The beam extraction/injection scheme can be used to accommodate a multi-object spectrograph, an integral-field spectrograph, and a long-slit spectrograph delivering high spectral resolution. This functional feature will enable the acquisition of velocity resolved data-cubes of galactic nuclear regions, quasars, and active galaxies which harbor black holes. Excitation and kinematic studies of galactic interstellar media and stellar and galactic outflows becomes possible.

1.2. Science Capability

A camera by its very nature is a multi-purpose instrument which can be used to conduct a vast array of investigations. The proposed instrument will conduct the program described in the DRM with great efficiency. Therefore, in this section, we will not dwell on the program outlined in the DRM. Instead, we discuss the design philosophy which has driven the specific hardware implementation discussed in the next section. We discuss how this philosophy permits a highly efficient execution of the DRM and creates new scientific opportunities for NGST. At the end of this section, we briefly discuss additional specific science investigations that our team will implement on NGST.

1.3. Design Philosophy

The proposed design was driven by the following considerations:

• *Maximize the field of view and number of deployed science pixels.* For most categories of astronomical objects, the science return from imaging experiments is proportional to the number of independent resolution elements in a picture. For example, in the investigations of cosmological supernovae, the evolution of galaxies with redshift, and their dependence on the local environment, the science return is proportional to the number of objects which can be observed. This quantity is in turn proportional to both the field of view and the number of resolution elements within that field. A greater number of objects can be studied in a given amount of observing time with a greater number of pixels. Since supernovae are bright, frequently outshining their host galaxies, they do not require a critically sampled focal plane to detect. Rather, the discovery rate is directly proportional to the area of sky covered, even if the image is severely undersampled. These considerations imply that the field of view of NGST must be maximized.

• *Provide multiple-plate scales.* Unlike ground-based telescopes, or any other large space astronomy missions, NGST will have an unprecedented range of operating wavelengths. The operational wavelength range of the near-infrared camera, 0.6 – 5.3 μm, encompasses nearly an entire decade of the spectrum. To fully utilize NGST, several plates scales and focal lengths are needed for critical sampling of the PSF at the bottom, middle, and top of the wavelength range. Multiple image scales are required to take full advantage of the unprecedented angular resolution provided by the 8 meter diameter NGST primary mirror.

• *Provide tunable filters.* The prime NGST bands contain a plethora of spectral lines and bands. These features trace molecular hydrogen, hydrogen recombination lines observable only from space, lines of atoms and ions in various ionization stages, molecular transitions in both the gas and solid states, and bands produced by refractory materials and ices (cf. PAHs, CO, CO_2 ices, etc.). NGST will be able to observe most of these features at high but arbitrary redshifts. Tunable filters that provide narrow-band imaging in $< 1\%$ pass-bands at arbitrary wavelengths are required to observe the spatial structure of sources.

• *Provide an independent FPA for guiding and fast steering mirror control.* Virtually by design, the fields chosen for the very deepest imaging experiments in any discipline will avoid bright stars in the field since scattered light from such objects can limit the depth of long exposures. Though fields in which no bright stars are present over the NGST FOV are likely to be extremely rare, it is precisely these statistically unlikely regions of the sky which are optimal for deep imaging. However, such fields may not contain stars bright enough to use for guiding. In our design, we will provide a single off-axis FPA used to guide on bright stars sufficiently far from the science aperture so that scattered light from a guide star will not limit the depth of the exposure.

• *Provide spectroscopic capability.* Spectroscopy is essential for the interpretation of the light received from astronomical sources. It has been 'traditional' at most facilities on both the ground and in space to provide independent spectroscopic and imaging instruments. On HST, and in the NGST preliminary planning, such a separation of functions has been implicitly imposed on the design. However, the need to constrain costs, risk, and maximize functionality dictates that a truly *integrated* design, in which both spectroscopic and imaging functions utilize the same detector assembly (focal-plane sharing), be seriously considered.

In prior applications, a separation of functions was mandated by differences in signal backgrounds. In both the visual and infrared wavelength regions, the backgrounds produced by airglow and a warm environment in imaging mode, are orders of magnitude higher than in spectroscopic applications. Thus, in traditional deployments, each function is provided by a facility instrument equipped with its own focal plane array.

However, from high Earth orbit, NGST will be limited by the zodiacal background which reaches a minimum of 2×10^{-5} erg sec^{-1} cm^{-2} sr^{-1} μm^{-1} near the Ecliptic poles around $\lambda = 3$ μm. In such a low-background environment, NGST will be detector limited, *even in imaging experiments*. Thus, there is no difference in the backgrounds encountered in imaging and spectroscopic applications.

The funding available for focal plane arrays is a fraction of the total budget. If independent focal planes are used for imaging and spectroscopy, the total number of pixels available must be subdivided between two or more special purpose instruments. Though each instrument can acquire data simultaneously in parallel, the total fields of view and number of pixels available to each function are reduced. Therefore, to maximize available pixels, we propose to *implement focal plane sharing* between the various prime-band observing modes of NGST. As discussed in the engineering section below, a simple optical design and reliable binary mechanism are used to implement focal plane sharing. Thus, observations can utilize the full focal plane in each mode.

Why should NGST be equipped with an 8k^2 FPA? Isn't 4k^2, or even 2k^2 large enough?

There are at least three reasons why NGST needs such a large FPA. First, an $8k^2$ FPA is needed to fully exploit the scientific potential of an 8 m diameter space-based near-infrared telescope. It is needed to achieve the science objectives outlined in the DRM with high efficiency. The large FPA can take full advantage of the focal surface that the NGST OTA can deliver. Second, the cost of this camera is small compared to the rest of the spacecraft. Third, by the time NGST is launched, large near-IR FPAs are likely to be common on most large ground-based telescopes. Without such an array, the NGST science instrument will not be state-of-the-art at the time of launch.

Risk in the $8k^2$ FPA design is mitigated by providing four independent detector quadrants to populate the $8k^2$ focal plane. Loss of a mechanism, FPA, or other module associated with a given optical path would only degrade the overall performance of the system by 25%.

1.4. Implementation of the DRM

The proposed instrument design can conduct the observations proposed in the DRM with very high efficiency and speed. In part the observing efficiency is a direct result of the large number of deployed pixels in each mode, in part because of the three available plate-scales, and in part because of the large $8'$ ($11.3'$ on the diagonal) field of view. Additionally, this design provides a large format and efficient detector array for spectroscopic observations.

Cosmology and the Structure of the Universe: The f/12 wide-field mode is well suited for surveys and searches for rare phenomena such as supernovae. The f/24 mode is ideal for gravitational lensing experiments in nearby clusters of galaxies. The f/64 mode is excellent for gamma-ray transient follow-ups. In all cases, the 8192 pixel format will enhance the rate at which the DRM can be executed, and produce higher quality science than possible with a smaller focal plane array.

The Origin and Evolution of Galaxies: The wide field of view, the tunable filters, and focal plane sharing with the MOS will facilitate all aspects of galaxy formation and evolution studies. The wide field will enable distant clusters and their evolution to be traced as a function of redshift. The narrow-band tunable filters and the MOS mode will enable the determination of redshifts, cosmic abundances, and stellar synthesis studies as functions of cosmic time. The wide-band filters will lead to the acquisition of the deepest images of galaxies possible. Galaxy formation and evolution as functions of environment and redshift can be investigated with ease.

The History of the Milky Way and Its Neighbors: The combination of wide field of view, tunable filters, and spectroscopic capability will enable studies of the physical and chemical processes in the Local Group. The origins and evolution of planets, stars, and galaxies and the process of cosmic chemical recycling will be investigated. The nature of the initial mass function, its dependence on environment, and the physical processes which determine it will be investigated. The wide-field mode will permit complete surveys of Local Group members at the full NGST angular resolution at many wavelengths.

The Birth and Formation of Stars: Direct imaging of star forming regions in specific tracers such as shock-excited lines like [FeII] and H_2, bands of solid and gas phase species such as CO and various ices, will be enabled by the combination of wide field of view needed to encompass entire star forming regions, tunable filter imaging, and spectroscopy of individual sources. The wide-field mode will permit complete surveys of entire molecular clouds and star forming regions, as well as substantial portions of the Galactic Center and inner Milky Way. High resolution spectroscopy with either a long-slit or an integral field unit will enable kinematic and excitation studies. The imaging mode will permit proper motion studies of outflows from young stars, old stars, post-main sequence objects, and their remnants; adding spectroscopy will lead to the determination of 3D flow fields.

The Origin and Evolution of Planetary Systems: The f/64 mode (possibly assisted with a simple coronagraphic mask) will permit the direct search for planets around the nearest stars, constrain the evolution of proto-planetary disks, and possibly lead to the detection of the first proto-planets or young planets. The MOS and spectroscopic add-ons will enable the detailed investigation of proto-planetary disks, hot Jupiters, extra-Solar planets, and brown dwarfs. The spectroscopic modes will enable study of pre-biotic molecules in molecular clouds, star forming regions, proto-planetary disks, and in the Solar System. Gravitational micro-lensing of Galactic center stars by foreground stars will be used to search for planets around the lensing stars down to the mass of Earth. Field of view is *the* critical parameter for this experiment.

1.5. Team Science

In addition to the core DRM science which includes major cosmology, extra-galactic, and some Galactic projects, our science team will design a program to address the origins of stars and planets. We will investigate star forming regions in the Milky Way and in nearby galaxies. These projects extend the current scope of the DRM. These team research areas include:

- *Deep infrared surveys of star formation regions:* We propose to assay the contents of entire molecular clouds down to the brown dwarf limit. NGST photometry will produce color-color diagrams needed to determine the evolutionary state of these stars. NGST spatial resolution is needed to resolve binaries and dense transient clusters where most stars appear to form and to conduct wide-field surveys over areas much larger than the isoplanatic patch. NGST sensitivity is needed to resolve low mass stars in distant parts of our galaxy and in nearby galaxies. NGST is needed for low resolution IR spectroscopy to determine stellar spectral types. The MOS is the ideal instrument for this purpose. (Extensive calibration of stellar spectral sequence in the IR is needed to conduct this aspect of the program.)

- *Obtain deep images and spectroscopy of proto-planetary disks seen in silhouette towards HII regions (cf. proplyds; Johnstone* et al. *1998; Bally* et al. *1998) to study their properties:* Observations with HST have shown that in the visible part of the spectrum, these disks are achromatic; that is, the grains in these environments have experienced substantial growth. NGST will extend the measurements into the infrared with better spatial resolution than provided by HST, and will provide spectroscopy which can be used to diagnose the grain size and composition, the presence and nature of ices, and other solid state properties.

- *Study the infrared properties of outflows and outflow sources as functions of proto-stellar age, mass, and environment:* The NGST tunable filters will provide the best opportunity to study the structure of shocks and of accretion disks in young star/accretion disk/jet systems. NGST will study many sources in Hα and other red nebular lines with three times the angular resolution of HST using the f/64 imaging mode. NGST will permit the investigation of outflows not only in the Solar vicinity, but anywhere in the Galaxy and in the Local Group. Therefore, for the first time, we can search for metallicity dependent effects on the properties of accretion disks and stellar jets.

- *Investigate the formation of high-luminosity, highly enshrouded high-mass proto-stars:* Radiation pressure acting on the infalling envelope prevents the formation of stars more massive than 10 to 100 $M_\odot$ by direct accretion. Bonnell et al. (1998) have proposed that such massive stars form in dense clusters only by 'proto-stellar cannibalism'. Stellar mergers are facilitated in such dense environments by the presence of accretion disks surrounding the lower mass proto-stars since the ratio of disk size to stellar separation in such clusters is only 1:10. NGST can search for the 10^{48} erg IR flares expected to be produced by the collisions of proto-stars in nearby starburst nuclei such as M82 or from much more distant starburst systems.

2. Engineering

2.1. The Design Concept

In this section we describe the proposed instrument design. The design is based on the Ball concept for the OTA, which consists of an 8 meter diameter filled aperture primary, secondary and tertiary mirrors, a fast steering mirror (FSM), and a deformable mirror (DM). It is assumed that this assembly delivers an f/24 beam. Ray-trace analysis of this optical train indicates that it is possible to illuminate a corrected and unvignetted field of view which subtends $10' \times 20'$ on the sky. It is assumed that this focal surface is shared. A $3'$ square region on one side of the illuminated field is devoted to the Multi-Object Spectrometer (MOS). A second $8'$ square region is devoted to the entrance aperture of the camera proposed here. The remaining off-axis portions of the illuminated field are used for the entrance apertures of one or more mid-infrared instruments operating beyond $\lambda = 5$ μm, and for the entrance aperture of an off-axis guide camera. Figure 1 shows this focal plane geometry projected onto the sky.

The theoretical diffraction limit of an 8 meter diameter NGST, θ, is given by $\theta = 0.0314 \times \lambda_{\mu m}$ arc seconds and the image scale produced by pixels with a pitch $P_{\mu m}$ (measured in μm) is given by

$$S = \frac{0.0258}{(f/ratio)} \times \; P_{\mu m} \qquad (arc\ seconds)$$

where $f/ratio = (e.f.l.)/D$. Table 1 lists the fields of view, diffraction limits, and sampling provided by 25 μm pixels for the principle imaging modes. Figure 1 shows these modes mapped onto the plane of the sky.

TABLE 1:NGST Prime-band imaging modes

Mode	FOV (arc min)	$\lambda_{optimal}$ (μm)	diffraction limit (arc sec)	sampling[1] (arc sec)	# pix
f/12	$8' \times 8'$	4	0.126	0.054	8192×8192
f/24	$4' \times 4'$	2	0.062	0.026	8192×8192
f/64	$0.75' \times 0.75'$	0.75	0.024	0.010	4096×4096

[1] Assuming 25 μm pixel diameter and pitch.

The central element of this design is a 4096×4096 pixel detector module which is used in each quadrant of the optical system. As discussed below, these modules can be populated by mosaics of either 16 1024×1024 pixel InSb ALLADIN class detectors or with 4 new Raytheon 2048×2048 pixel InSb focal plane arrays (FPAs). Both classes of detector are assumed to have 25–27 μm pixels. The ALLADIN class detectors are available today.

Alternatively, the detector modules can be populated by 16 Rockwell 1024×1024 pixel HgCdTe or 4 2048×2048 pixel HgCdTe detectors. These detectors must have broad-band response over the 0.6 to 5 μm wavelength range. However, performance to 0.6 μm has not yet been demonstrated.

2.2. Optics

The first major optical element in the camera encountered by light arriving from the NGST OTA is the roof prism located near but not exactly at a focal surface. This roof

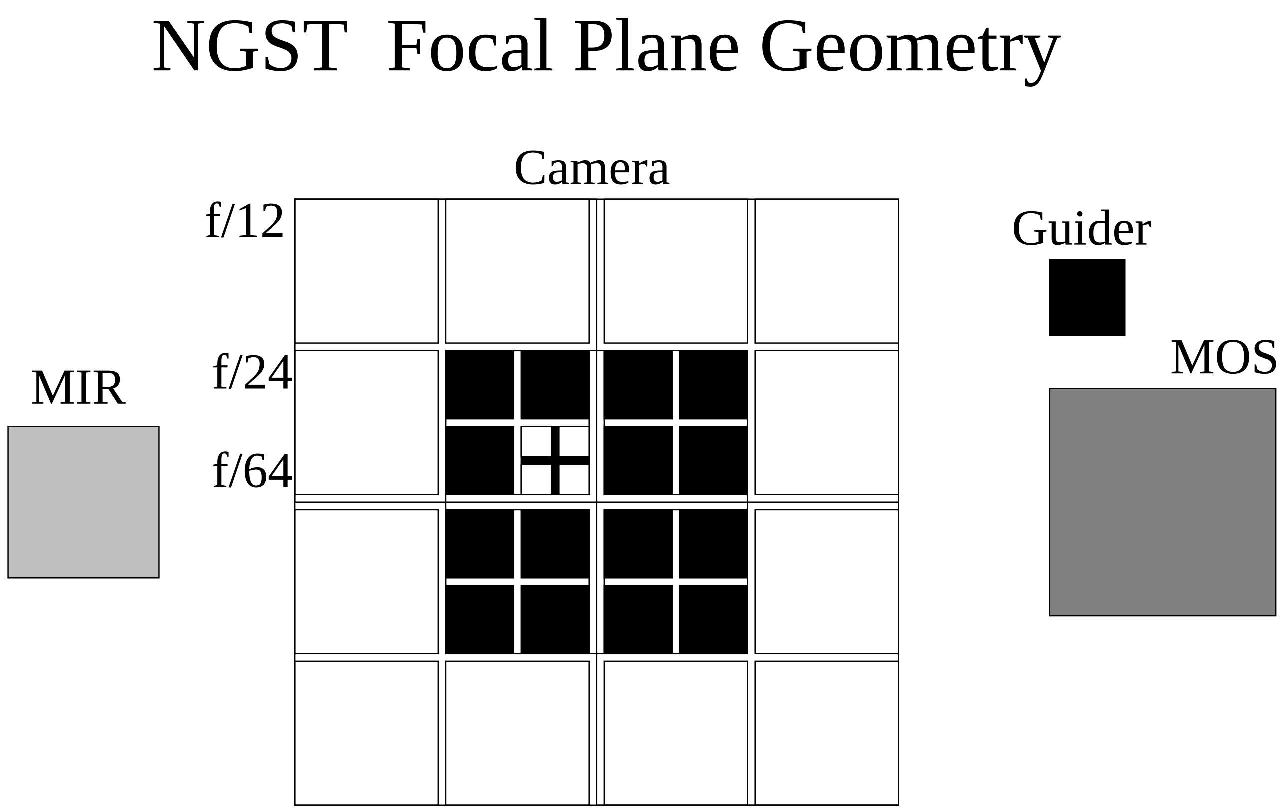

Fig. 1.— *The NGST focal plane projected onto the plane of the sky showing the 3′ MOS entrance aperture, the imaging entrance aperture showing the fields of view of the f/12 (largest), f/24 (black squares), and f/64 modes (smallest pattern of white squares). The camera focal plane is shown with 2048×2048 pixel FPAs. The gap dimensions are exaggerated. If 1024×1024 pixel FPAs are used, each illustrated square would contain four smaller edge-butted FPAs. The entrance apertures of the mid-infrared camera and the off-axis guider aperture are also shown.*

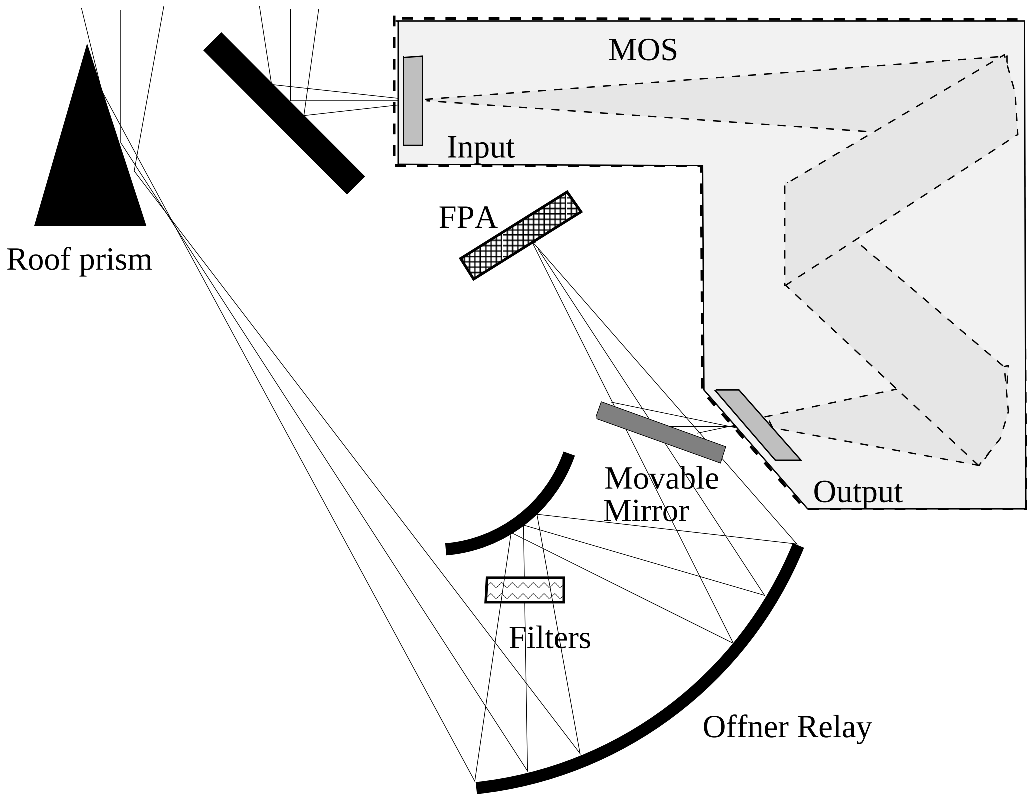

Fig. 2.— *A schematic illustration of focal plane sharing between the f/24 camera mode and the MOS. Light from the OTA arrives from the top. For direct imaging, light is reflected from a roof prism (the angle of this prism is exaggerated) which illuminates four independent camera units. In each unit, light passes through the focal plane and enters a 1:1 Offner relay. Filters are mounted in the pupil just in front of the Offner secondary where the Offner primary forms an image of the NGST primary mirror. The movable mirror is retracted from the beam for imaging. For MOS observations, this mirror is inserted into the beam. The MOS is fed by an independent light path which is coupled to the camera FPA assembly by this movable mirror.*

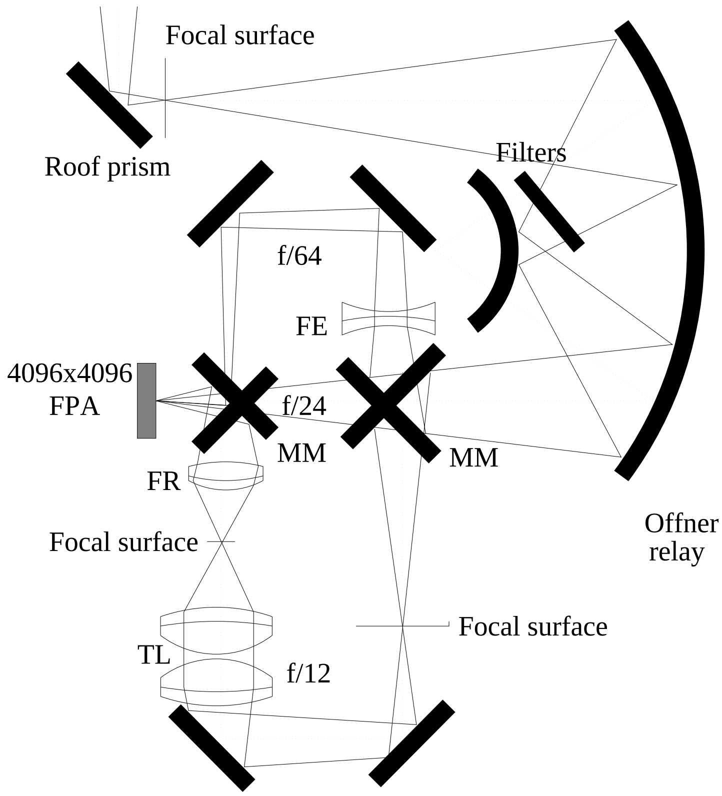

Fig. 3.— *A schematic illustration of the mechanisms and optics required to change the plate scales and focal lengths in one quadrant of the camera. The default beam which comes straight through the Offner relay is f/24. Movable mirrors (MM) can be inserted into the beam to provide different f/ratios. When the beam is deflected up, it passes through a focal extender (FE), and reflected from flats which bring the beam to a focus on the FPA. When the beam is deflected down, it passes through a transfer lens (TL) and a focal reducer (FR) before being brought to a focus on the FPA. All three modes are confocal. Though the focal extender, focal reducer, and transfer lens are shown here as refractive elements for clarity, they will be implemented as reflecting elements, combining the functions of the fold mirrors and these lenses.*

prism sub-divides the incident beam into four separate light bundles.

After reflection from a facet of the roof, each light bundle feeds a 1:1 Offner optical relay consisting of a pair of 360 mm $\times$ 360 mm confocal concave spherical mirrors on the input and output sides and a 60 mm convex secondary. An entrance pupil is formed near the secondary mirror where the light bundle is less than 30 mm in diameter, permitting small-diameter (< 30 mm) filters to be used with the large FPA assembly. The convergence and divergence angle of the light bundle is small enough to permit the use of $< 1\%$ pass-band filters at this location. Therefore, this is where wide and medium band fixed wavelength filters are mounted in a rotary filter moving mechanism. A second mechanism carries the Fabry-Perot type tunable filters. The output side of each Offner relay directly illuminates a 4096×4096 pixel detector assembly with an f/24 beams.

The f/12 and f/64 modes are implemented by the introduction of pairs of flats into the beam between the output side of the Offners and the detector assemblies. These flats, either co-mounted on the same binary mechanism, or using independent but lighter mechanisms, serve to extract and reinject the beam into the optical path. The maximum beam diameter in the region of pick-off and reinjection is 130 mm.

To implement the f/12 mode, the light reflected from the first (pick-off) mirror passes through a relay lens used to extend the optical path. Then the beam is converted from f/24 to f/12 in a focal reducer. Flat mirrors, including a re-injection mirror, illuminate the FPA assembly. The relay optics and the focal reducer consist of either refractive or reflective optics. We have completed a design of an all refractive focal reducer which can illuminate the entire focal plane assembly. The design of an all reflective focal reducer plus relay is in progress.

Implementation of the f/64 mode requires only the use of a focal extender. This mode utilizes only one quadrant of the camera and illuminates one 4k FPA assembly. After reflection from the pick-off mirror introduced into the f/24 beam, the light bundle passes through a focal extender, followed by a set of flat mirrors which absorb the extra optical path needed to bring the f/64 beam into focus on the detector assembly. The f/12, f/24, and f/64 modes are confocal. However, minor focus adjustments to accommodate path length variations in the f/12, f/24, and f/64 modes can be accommodated by moving the Offner relay with respect to the detector assembly.

Ray-tracing has demonstrated that diffraction-limited performance can be achieved over the proposed fields of view in all three camera modes. Furthermore, is has been shown that the required optics and mechanisms can be packaged within the volume and mass envelopes envisioned for the NGST ISIM module. The optical design inherits its legacy from the HST project.

The detector assembly will also serve as a wave-front sensor used to monitor the performance of the NGST OTA. The wave-front sensing function can be used to optimize the figure of the primary mirror and to control the deformable mirror to produce the best point-spread function. Three types of wave-front sensing can be implemented: analysis of in- and out-of-focus images of point sources, dispersed fringe techniques using grisms mounted on the filter wheel, and imaging the in- and out-of-focus images produced by a Hartmann mask and/or phase mask located in the Offner pupil and mounted in the filter wheel.

2.3. Mechanisms

There will be only two types of mechanisms used to move optical elements into and out of the beam: filter wheels and binary mechanisms to insert and retract optics, plus mechanisms to adjust focus. Thus, the design, engineering, and performance verification of these mechanisms will be re-used in many components. Ball Aerospace Corporation has built similar mechanisms for instruments which are now operating in the Hubble Space Telescope. These mechanisms are reliable in space. With appropriate design modifications, their use in a cryogenic environment poses little risk.

When possible, mirror insertion mechanisms will rotate optical elements into the beam *parallel* to their surfaces. In this configuration, optical paths are not effected by slight placement errors.

A rotary filter mechanism is required in each Offner to accommodate the medium and wide band filters. In addition to providing wide and moderate band-width imaging, these filters act as order sorters for the tunable filters. The Goddard tunable filters are mounted on their own mechanisms which insert them into the beam near the filter wheels. The optimal geometry to minimize ghosts and internal reflections is being explored. In one possible configuration, filters are mounted on the input-side of the Offner just ahead of its secondary. The tunable filters are inserted into the beam just ahead or behind the fixed pass-band filters. Thus, both tunable and fixed-passband filters are located close to the Offner pupil and require clear apertures of less than 30 mm. The filter wheels will have between 12 to 18 filter mounting slots.

Switching between the various camera modes, and between imaging and spectrographic functions is provided by binary mechanisms which insert pick-off mirrors in the default f/24 optical path. Only the in-beam positions are critical; the positioning of the optics in the retracted position is not. The mechanisms will be loaded so that in the event of component failure, they will settle into the retracted position. Back-up actuators will be provided to prevent sticking of elements in the default f/24 beam.

Each camera quadrant will be equipped with focusing mechanisms to correct for on-orbit dimensional changes and slight variations in the optical paths associated with the various camera modes. A stepper-motor will drive a linear actuator mounted behind the output side of each Offner relay to enable motion along the axis passing through its center to the middle of the detector array. Such focusing mechanisms have been used successfully in a variety of flight instruments built by Ball Aerospace Corporation.

Implementing focal length and plate-scale changes with pick-off mirrors, focal reducers and/or extenders, and re-injection mirrors is cheaper then the cost of replicating the focal plane arrays and associated optics.

2.4. Using the FPA with the MOS

The multi-object spectrometer (MOS) has its own entrance aperture next to that of the camera (Figure 1). The MOS entrance aperture directs light from various field points to a spectrometer (possibly using a computer controlled micro-mirror array). When the camera FPA is devoted to the MOS, the output beam of the spectrometer is injected into the camera optical path feeding one quadrant of the FPA. MOS beam insertion is achieved by a binary mechanism introduced into the camera between the roof prism and the input of one of the Offner relays. Two or possibly all three f/ratios thus become available for MOS spectroscopy, providing three possible pixel scales to accommodate different wavelength regions with comparable resolution or to provide variable spectral resolution at a given wavelength. MOS spectra can be filtered with any of the camera broad or medium pass-band filters to limit order overlap. In this design, the remaining three quadrants of the camera are available for either parallel imaging programs or for spectroscopy using the post-Offner spectroscopic apertures.

Focal plane sharing between imaging and spectroscopic modes is the most cost-effective way to provide large numbers of pixels for both modes. The cost of the mechanisms and optics required to implement focal plane sharing is far lower than the cost of duplicating the focal planes and associated electronics (see Table 2 for details). In addition to the MOS, light can be extracted after the Offner relays, processed by instruments provided by other groups, and re-injected to utilize the camera FPAs. It is relatively inexpensive to implement an integral-field spectrograph, and long-slit spectrograph, and/or a coronagraph with such mechanisms.

2.5. Instrument Packaging

Either a graphite-epoxy or a beryllium truss structure will be used to support the optical elements, filter-wheel mechanisms, beam extraction/injection mirrors and associated mechanisms, and detector assemblies. This optical bench design will follow the proven concepts used by Ball Aerospace Corporation for HST instruments. Each instrument mode will include baffles and masks to control starlight and unwanted reflections. In addition to an instrument cover, baffles will be installed between the four instrument quadrants, and

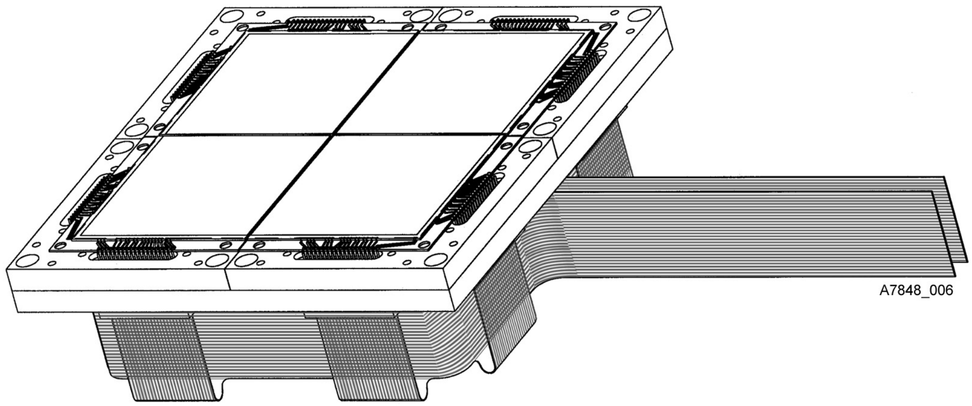

Fig. 4.— *The Ball 4096×4096 detector module, shown populated with edge-buttable 2k FPAs. The package is about 110 mm on a side.*

black plates will separate the various possible optical paths.

2.6. Detectors

The optical design, mechanisms, and bench use proven optical and mechanical principles. Furthermore, preliminary design studies have demonstrated that all elements of the design described here are feasible and can be fabricated for reasonable cost. The use of proven components and a redundant architecture provide a low risk opto-mechanical system. However, large quantities of low read-noise (< 4 e^-/read), low dark-current ($<$ 0.01 e^-/second), large-format ($>1024^2$), and broad-band (high QE in the wavelength range 0.6–5.3 μm) FPAs are required and remain a critical item for this design.

2.6.1. *The Science and Technical Case for Large Detectors.*

Large-format detectors are required to take full advantage of the available focal planes in both imaging and spectroscopy. The Ball designed NGST OTA delivers a roughly 10–20′ FOV. In the proposed design, this area is subdivided between the entrance aperture of the camera, and the entrance aperture of the MOS. For a diffraction limited PSF at $\lambda = 2$ μm, this leads to an FOV/PSF ratio of about 10,000. Spectrographs can deliver an even larger number of independent data elements.

The science return of many classes of astrophysical and Solar System remote sensing experiments is directly proportional to the number of pixels available and/or delivered field of view of an image or spectrum. Examples include imaging studies of distributed and randomly placed objects such as distant supernovae, galaxies in clusters, stars, emission nebulae, and planetary surfaces, plus a variety of spectroscopic investigations such as multi-object spectroscopy, and spectroscopy requiring simultaneous broad wavelength coverage and high-dispersion, or three-dimensional integral-field spectroscopy.

2.6.2. 1k vs. 2k FPA Issues

The full and efficient extraction of the useful information delivered by future space telescopes requires the fabrication of mosaics of smaller detector arrays. The number of required components, the cost of device selection and verification, labor associated with fabrication, and overall risk and complexity are minimized by maximizing the dimensions of the individual detector elements. An $8k^2$ pixel mosaic requires 64 individual sub-arrays if fabricated from $1k^2$ FPAs. However, only 16 $2k^2$ elements would be required. Figures 5, 6, and 7 in the Appendix illustrate the use of 64 $1k^2$ FPAs or 16 $2k^2$ FPAs in imaging mode.

For most imaging applications, the adverse effects of gaps inherent to mosaics can be ameliorated by data acquisition methods such as dithering in which the target position is shifted with respect to the gap location as a series of exposures are accumulated. However, gaps have severe and adverse effects for most spectroscopic applications where the relative positions of the entrance aperture and focal plane are fixed by the optics geometry. In this latter case, it is especially important to minimize both the number of gaps and their covering factor.

Packaging constraints imply that the gaps between non-edge-buttable elements have to be about 3 mm to provide enough room to bring out the electrical leads needed for each individual array. On the other hand, edge-buttable FPAs will have gaps smaller than 1 mm. For a four quadrant FPA package such as shown in Figure 4, each quadrant requires either 4 2k format chips, or 16 1k format chips. In the former, all gaps in the interior of the assembly can be held to edge-buttable tolerances and can be smaller than 1 mm. For the latter configuration, there must be at least two wide gaps in the interior portion of the array with a width of 3 mm or more. Though these packaging issues do not impact imaging severely, they do have a serious impact on MOS applications since the larger the dead-space, the greater the chance of losing part or all of some spectra.

A second consideration is the complexity, schedule, cost, and risk associated with the handling, testing, and packaging of a larger number of smaller elements. In addition to the extra labor associated with handling the larger number of parts, there is increased risk as a direct result of handling and packaging. Handling is likely to induce greater chip mortality; the large number of leads increases the likelihood of electrical cross-talk and increases the complexity of the array control electronics. With finite process control, problems associated with lack of FPA surface coplanarity and intra-module FPA alignment are likely to increase as the FPA parts count grows. The impacts of these packaging related issues are likely to manifest themselves in the greater complexity of FPA calibration. For example, row and column mis-alignment errors will require a larger effort in astrometric calibration in imaging mode and wavelength calibration in spectroscopic mode. Finally, if the array is to be populated with 64 FPAs, there is increased likelihood that FPAs will originate from different processing lots. This will increase the variability of FPA parameters such as dark current, read noise, and responsivity.

These considerations imply that the FPA can use either 1k or 2k format detector elements. However, lower packaging cost, decreased risk, and better geometric filling factor and smaller gaps favor the utilization of 2k technology. Technology readiness favors the use of 1k existing format ALLADIN technology.

2.6.3. Detector Material Selection Issues

There are several classes of detectors available for use on NGST in the 0.6 to 5.3 μm wavelength range: InSb, HgCdTe, PtSi, Si photodiode arrays, and multiple-quantum well devices (MQW). So far, neither PtSi nor MQW have been shown to possess high QE over the large range of wavelengths needed for NGST FPA applications. Thus no further consideration will be given to the use of PtSi or MQWs. *The available 1k format of InSb and broad-band HgCdTe detectors currently under development are suitable for use in the proposed instrument.*

High sensitivity (QE $>$ 80%), low read-noise ($<$ 4e/read), low dark-current ($<$1e/minute), broad-band (0.6 to 5 micro-meter), large-format (1k or 2k format) devices which can be used at about 30 Kelvin where the passively cooled NGST is likely to operate are needed.

It is highly desirable to fabricate mosaics from the largest available individual detector elements. Broad-band (0.6 to 5.3 micro-meter) InSb devices and moderate-band (0.8 to 2.4 micro-meter) HgCdTe detectors are now available in 1k square formats. The development of 2k HgCdTe devices tailored to cover the entire 0.6 to 5.3 μm wavelength range is progressing rapidly. However, the operational properties of these devices are at present unknown. Experience with the smaller format near-IR NICMOS legacy HgCdTe detectors has shown that they are more difficult to operate than the comparably sized InSb chips.

Pixel size places a constraint on the selection of the FPA technology. The ALLADIN class InSb devices can be fabricated with pixel dimensions in the range 25–27 μm. The instrument design in this study is optimized for this pixel scale.

Existing HgCdTe devices used in astronomy have an 18 μm pixel size. Modulation transfer function (MTF) measurements are needed to determine quantitatively the degree of MTF loss resulting from use of 18 μm pixels relative to the larger 25 to 27 μm pixels. If this chip were used (in its broad-band incarnation) to populate our instrument FPA, then the plate scale, fields of view, and optimum operating wavelength would all be decreased by a factor of 0.56–0.6. On the other hand, it is in principle possible to accommodate the smaller pixel scale provided by the HgCdTe technology by decreasing the focal ratios of the optics by the same fraction. However, the ray-tracing analysis has shown that is is not possible to illuminate the full 4096×4096 subarrays below f/9 without producing significant off-axis aberrations. To accommodate the proposed wide-field mode, the f/ratio would have to be decreased to about f/8.6. Full aberration compensation would then require adding additional optical elements into each focal reducer used in our design. This modification would increase cost, degrade performance by increasing the number of optical surfaces encountered by the incident beam, and would increase the risk to the project.

These considerations place the following constraints on the two mature detector technologies:

For InSb it is desirable to develop 2k format FPAs. For HgCdTe, broad-band FPAs with high QE from 0.6 to 5.3 μm must be developed, preferably in a 2k format. Finally, it would be desirable to produce these FPAs with at least 25 μm pixels to permit aberration-free illumination of large FPA assemblies. It has to be verified that the dark current produced by 25 μm pixel HgCdTe FPAs is competitive with that of existing InSb FPAs.

Thus, the optical design considerations favor the use of InSb technology at present. However, we conclude that it is crucial to support the development of both broad-band HgCdTe AND InSb to the point where functioning science grade devices in large formats can be evaluated. Only then can the best technology for space-based detector applications be fairly chosen. Nevertheless, we want to emphasize that *our instrument concept is sufficiently flexible that either technology can be used.*

2.6.4. The Cost of Large Format InSb FPAs

Though no 2k format InSb FPAs exist, we have explored the cost and risk associated with pushing the development of these large-format devices. The fabrication cost of three lots FPAs is about 2M$ and devices would be available within less than 18 months of the award of a contract. There is greater risk associated with the use of the 2k FPAs because they are not available today. However, if such FPAs were to be available, there would be considerably less risk and cost associated with the handling of four times fewer devices needed to populate the NGST science instrument module. However, space qualified chips in sufficient quantity, and in time to use on NGST will only be available *if funding is made available to push the 2k chip development effort forwards within the next 12 to 18 months.*

It is likely that by the time NGST flight hardware has to be delivered in approximately

5 years, large-format InSb detectors will be available. The next generation high-dispersion near-infrared spectrometers being considered for 8–10 meter class telescopes would benefit greatly from the large-format detectors. The history of 15 years of infrared FPA development shows that like silicon computer chips, near-IR detector development follows Moore's law — the number of available pixels doubles every 18 to 24 months. Extrapolating this tendency indicates that large-format arrays will likely be available in time to incorporate them into NGST flight components.

2.7. De-scope Options

The CU/Ball camera concept will produce a highly capable and powerful scientific instrument. However, design-to-cost may not allow the funding of the instrument as envisioned here. Our design is sufficiently flexible so that it can be de-scoped to fit a smaller budget. The degradation of capability as a function of de-scoping is graceful. Below, we outline several de-scope options:

• **4k×8k Option:** By elimninating two quadrants of our design and leaving two quadrants, the camera can still provide $4' \times 8'$ FOV in the f/12 mode. All spectroscopic and imaging functions are retained with a smaller field. In this mode, the mechanism count, optics parts, and number of required FPAs declines by a factor of nearly two.

• **4k×4k Option:** A single quadrant instrument would provide a $4' \times 4'$ FOV in the f/12 mode and alternate spectroscopic modes can still be retained. This option would require only about 1/4 of the number of components of the original design. The roof prism is eliminated entirely. In both of these de-scope options, three plate-scales and f/ratios are provided, and the detector module still serves as the sensor for a MOS and other spectroscopic functions.

The de-scope options carry approximately the same design and engineering costs as the full design, but do have smaller parts counts and lower mass and power requirements. Thus the total instrument and project costs do not decline as rapidly as the degradation of science capability. However, these de-scoped options still retain the essential functional elements of our concept which include:

- Focal plane sharing between imaging and spectroscopic functions. The full complement of NGST prime-band FPAs are available for each major function of the observatory.
- Three f/ratios and plate scales to provide critical sampling for both imaging and spectroscopy over the entire 0.6–5.3 μm band.

• **Bare-bones Camera Option:** Finally, it is possible to consider a bare-bones camera concept in which the FPAs serve only the imaging functions of the observatory.

Either a three, two, or one focal length variation of this option is possible. A single mode option would consist of nothing more than an FPA and a filter wheel mounted at the focus of the NGST. In its simplest form, this mode would sense a $4' \times 4'$ field of view with one 4096^2 FPA module. Our choice of optimal operating wavelength for this option would be 3 μm to take advantage of the 'cosmological window'.

In a slightly more complex form, an 8192^2 system could be implemented with four Offner relays and four separate FPA packages. The difference between this 'bare-bones-plus' option and the complete camera concept is the lack of focal plane sharing and plate scale changing optics. However, we do not see this as a cost-effective choice since the cost of the focal plane sharing and plate scale changing hardware is very small compared to the cost of the instrument.

Though the cost of the last option is likely to be about 50% of the complete instrument, this configuration is not well matched to the large investment to be made in the NGST OTA. The cost of the minimum configuration represents only about 10% of the cost of the OTA; and it will only yield about 10% of the science possible with the complete instrument.

2.8. Development Schedule and Integration & Test Plan

The major items in the development schedule include:

• Complete design and interface specifications, mating to the OTA, and other instruments such as a coronagraph and spectroscopes. During this phase, close collaboration with other instrument groups (providing the spectrographs and long-wavelength instruments) is needed.

• Design a detector package which can utilize 1k or 2k format InSb, or HgCdTe devices. The final choice of the flight detectors will be made at the last possible time based on the then state-of-the-art detectors.

• Develop a detector test facility to verify FPA performance.

• Develop the IR array control and readout electronics on a platform compatible with RAD 6000 standards.

• Integrate pre-flight hardware components of one complete quadrant of the camera, including optics, mechanisms, filters, and control electronics into a ground-based test dewar ('Proto-CAM') which can be taken to a large ground-based telescope for operations and verification. This step will give on-sky experience with the NGST camera design. It will verify the detector package concept, the operation of the tunable and fixed-band filters, and demonstrate focal plane sharing. Since the use of this instrument on the ground will be restricted to imaging below 2.4 μm by thermal emission, focal plane sharing with a long-wavelength spectrograph is the only way to verify the long wavelength performance of the system.

• Finalize the design of the flight hardware, and procure all flight components. Test individual optical and mechanical sub-assemblies on a component by component basis.

• Fabricate the optical bench, instrument enclosure, individual optical elements, mounts, and mechanisms.

• Integrate flight instrument. Freeze the detector technology. Deliver flight hardware to Goddard for integration into NGST.

• Retrofit 'Proto-CAM' with exact copies of the flight hardware. Use this instrument to continue software development and calibration activities.

3. Cost Estimate

Total cost of the 8192×8192 pixel design is estimated to be 103.55 M$ without contingency or detector development. The cost of the de-scope options are 78.45 M$ for the 8192×4096 pixel option, and 57.88 M$ for the 4096×4096 pixel option. These options include the mechanisms and optics required to implement focal plane sharing. These costs are detailed in Table 2 below.

The bare-bones 4096×4096 pixel camera option abandons focal plane sharing. By saving on the optics and mechanisms required to switch beams from imaging to detector modes, the cost decreases to about 42.83 M$. If this mode were to be implemented, the NGST prime-band spectrometers would each have to provide their own FPAs. However, the cost of these FPAs, associated electronics, and optical mounts to the NGST project are likely to far exceed the savings. Thus, *focal plane sharing is the most cost-effective way to provide both imaging and spectroscopic functions in the NGST prime band.*

3.1. Details

Since this is an un-funded design study, we do not have hard figures on component costs. Therefore, we will base our estimates on some general guidelines. These are:

TABLE 2: NGST Integrated Camera Cost Estimate

Item	Cost: $8k^2$ $\times 10^6$\$	$4k\times 8k$ $\times 10^6$\$	$4k^2$ $\times 10^6$\$	Bare-bones $4k^2$ $\times 10^6$\$	Basis
Tunable filters	-	-	-	-	GSFC (GFE)
Fixed-band filters	0.5	0.25	0.13	0.13	NICMOS, WFPC2
Offner relays	0.4	0.3	0.2	0.2	
f/12	1.3	0.8	0.4	-	
f/64	0.7	0.7	0.7	-	
Baffles	0.5	0.35	0.2	0.2	
Optical design	4.5	4.5	4.5	2.0	
Optical test	1.5	1.0	0.6	0.6	
Mech mounts	1.5	1.0	0.6	0.6	
Optical Bench	4.7	3.5	2.5	2.0	Ball
Enclosure	1.9	1.4	1.2	1.0	ACS
FPA Assemblies	12.0	8.0	6.0	6.0	Vendor estimate
Detector electronics	3.0	1.5	0.8	0.8	ACS
Electronics	9.4	6.4	3.4	3.0	Ball
Mechanisms	7.6	5.0	3.0	3.0	ACS, SIRTF
Cooling System	1.2	0.9	0.8	0.8	Ball
Calibration	0.5	0.5	0.5	0.5	COS
I&T	17.2	13.2	9.2	7.2	Ball
Q&A	8.1	6.1	4.1	3.5	Ball
Systems engineering	10.3	8.3	6.3	4.3	Ball
Management	14.5	12.5	10.5	5.0	Ball
Software	2.25	2.25	2.25	2.0	Ball
TOTAL	103.55	78.45	57.88	42.83	

Explanations: The cost-estimates are based on the results of consultation with Ball Aerospace Corporation. They are CU estimates, and therefore not official price quotes for this project.

For the full (8192×8192 pixel) design, the mechanism count consists of 8 binary mechanisms located after the Offner relays, 4 shutters, two filter wheels in each Offner, and one large binary mechanism to switch the input to the MOS. Thus, there are 21 mechanisms. Fixed-band filters cost 0.01M\$ (flight qualified). It is assumed that flight qualified tunable filters are provided GFE. Two are needed in each leg for a total of 8.

The line called 'Optics total' represents the sum of the four sub-categories listed above this line. The total number is included in the total cost.

For the pricing in Table 2, we assume that 1024×1024 pixel ALLADIN class detectors will be used. Costing is based on the current unit cost of these devices for small quantities assuming unit costs of 0.2 M$ each. Controller electronics costs are also based on Mauna Kea IR and Leach unit costs. In both items, there may be price breaks associated with the large orders.

It is assumed that in addition to the 64 flight detectors, there will be 32 flight spares in two complete detector assemblies. Furthermore, we assume that there will be chip mortality associated with handling. Thus, we estimate that an additional 32 chips will need to be processed. Total cost of detector packaging is assumed to be 2.5 M$ per flight unit.

The alternate route is to develop the 2048×2048 pixel technology. This requires some up-front development costs. Raytheon has provided an informal bid. The processing of three lots of 2k chips is expected to cost under 3M$. Though the first one or two foundry runs are likely to only produce engineering grade devices, it is likely that science grade chips would be produced by a third run. Additional lots will be needed to obtain the 16 science grade FPAs needed for flight and to procure flight spares. These lots would be acquired under an NGST flight hardware procurement contract.

Since the labor associated with these operations is, to first order, proportional to the number of devices being processed, and not the size of these devices, there may be substantial savings in device selection, testing, packaging, and integration with the larger format detectors. Furthermore, there will be a lower mortality due to the smaller number of components involved. There is also decreased risk due to the lower parts count and lower probability of problems arising during systems integration. With the smaller chips, there is more wiring, and more complexity in the electronics. Furthermore, more effort has to be devoted to calibration.

Since 2k InSb devices have yet been fabricated, there are many unknowns. Therefore, it is very hard to quantify the true costs and savings associated with the use of 1k or 2k formate detectors.

The total cost is (103.55 M$).

For the de-scoped (4096×4096 pixel) and (2048×2048 pixel) designs, the costs reflect the decreased parts counts and the slightly lower cost of design, engineering, and management.

4. Conclusions

The key results of our study are:

• *Implement large numbers of pixels:* An 8192×8192 pixel focal plane sensing an $8' \times 8'$ field of view is feasible and highly desirable on NGST. Risk is mitigated by providing four nearly identical 4096×4096 pixel camera modules.

• *Focal plane sharing is cost-effective:* In the NGST prime bands, focal plane sharing between imaging and spectroscopic functions is the most cost-effective means of implementing NGST science. The cost of the mechanisms and optics required to implement focal plane sharing is less than the cost of duplicating the detector arrays. Focal plane sharing provides access to all camera modes, and minimizes duplication of effort. Focal plane sharing maximizes the pixels available for each observatory function.

• *Multiple plate-scales are needed:* Three plate-scales are needed to effectively utilize the resolution provided by NGST over its prime wavelength range. It is cheaper to build the mechanisms needed to implement focal length changes in the optics than to replicate detector modules. Focal plane sharing maximizes the pixels available for each plate scale.

• *The development of 2048 pixel InSb should be funded now:* The cost of selection, handling, packaging, wiring, and electronics is far less for 16 2048 pixel InSb FPAs than for 64 1024 pixel devices (plus appropriate spares). These costs are nearly independent of the size of the FPA; instead, they depend on the number of FPAs being processed. Unfortunately, we have not been able to quantify this cost difference with any degree of reliability. Nevertheless, for a project as large as NGST, it is our feeling that the cost benefit of using fewer large-format FPAs is greater than the extra cost of developing the large-format devices. InSb has been proven to have good response over the NGST prime band. Furthermore, it is easier to illuminate a wide-field array of 25 μm FPAs than 18μm FPAs. MTF loss due to smaller pixels has not been measured and any resulting effect on science return has not been quantified. Thus, the use of large format InSb FPAs is preferred.

• *Implement a separate detector for guiding:* Deep imaging requires the avoidance of bright stars. Guiding requires such stars. It is scientifically desirable to provide a separate off-axis sensor for guiding and control of the deformable mirror and the fast steering mirror. A quantitative analysis of light scattering in the final NGST optical layout is needed to determine the degree of impairment that will result from the presence of stars bright enough to be used for guiding.

5. References

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6. Appendix 1: The cost of 2k InSb Development

Figure 5 shows the HST image of the dust pillars in M16. Figure 6 shows a simulation of a single exposure obtained with an 8192×8192 pixel camera populated with 64 $1k^2$ FPAs. Figure 7 shows the results of an observation obtained with the camera populated with 16 $2k^2$ FPAs.

Ball Aerospace Corporation's 2k detector development effort has demonstrated the feasibility of 2k InSb device production. A 2k silicon multiplexer and readout integrated circuit (ROIC) suitable for bump-bonding to InSb detector wafers has been designed and fabricated. Johnson-Mathey Electronics (JME) has produced InSb wafers with dimensions suitable for mating to these multiplexers. Raytheon (Santa Barbara Research Center - SBRC) is ready to proceed with the hybridization (mating of the InSb wafers to the ROIC). Thus, all technical elements required for the fabrication of functioning 2k InSb devices are in place.

Ball Aerospace's initiative, funded jointly by GSFC, Raytheon, and Ball Aerospace, to develop a 2k×2k FPA broke new ground for large-scale ROIC fabrication. The success of Raytheon's (formally Amber Engineering's) RICL circuit fabrication process produced the STAR chip to enable the NGST 4k×4k FPA assemblies based on 2k×2k ROICs with 25 μm pixel centers. Prior to this activity, the largest FPA produced for any candidate detector technology was based on a 1k×1k ROIC. [A 2k×2k ROIC for 18 μm pixel spacing has since been produced by Rockwell Science Center.]

The main goal of demonstrating a proof-of-concept of large, high density input cell density for IR detectors on the scale of the NGST FPA was a success. But as occasionally happens with a new, aggressive ROIC, the first design was not completely electrically operable. In this case the circuit has a design anomaly that keeps the detectors from resetting properly. All the other electrical functions work including the asynchronous windowing (guiding) feature.

A proposed second ROIC design iteration would fix the reset anomaly, reduce the transistor count, and increase fabrication yield by simplifying the windowing circuit. In the interest of broadening STAR's utility, design features relating to performance parameters of concern to ground-based astronomers such as frame read rate and well fill will be incorporated. STAR2 could include user-selectable multiple readout paths (up to 32) and possibly unit cell gain settings.

An alternate approach to 25 μm pitch 2k×2k ROICs starts with ALLADIN follow-on

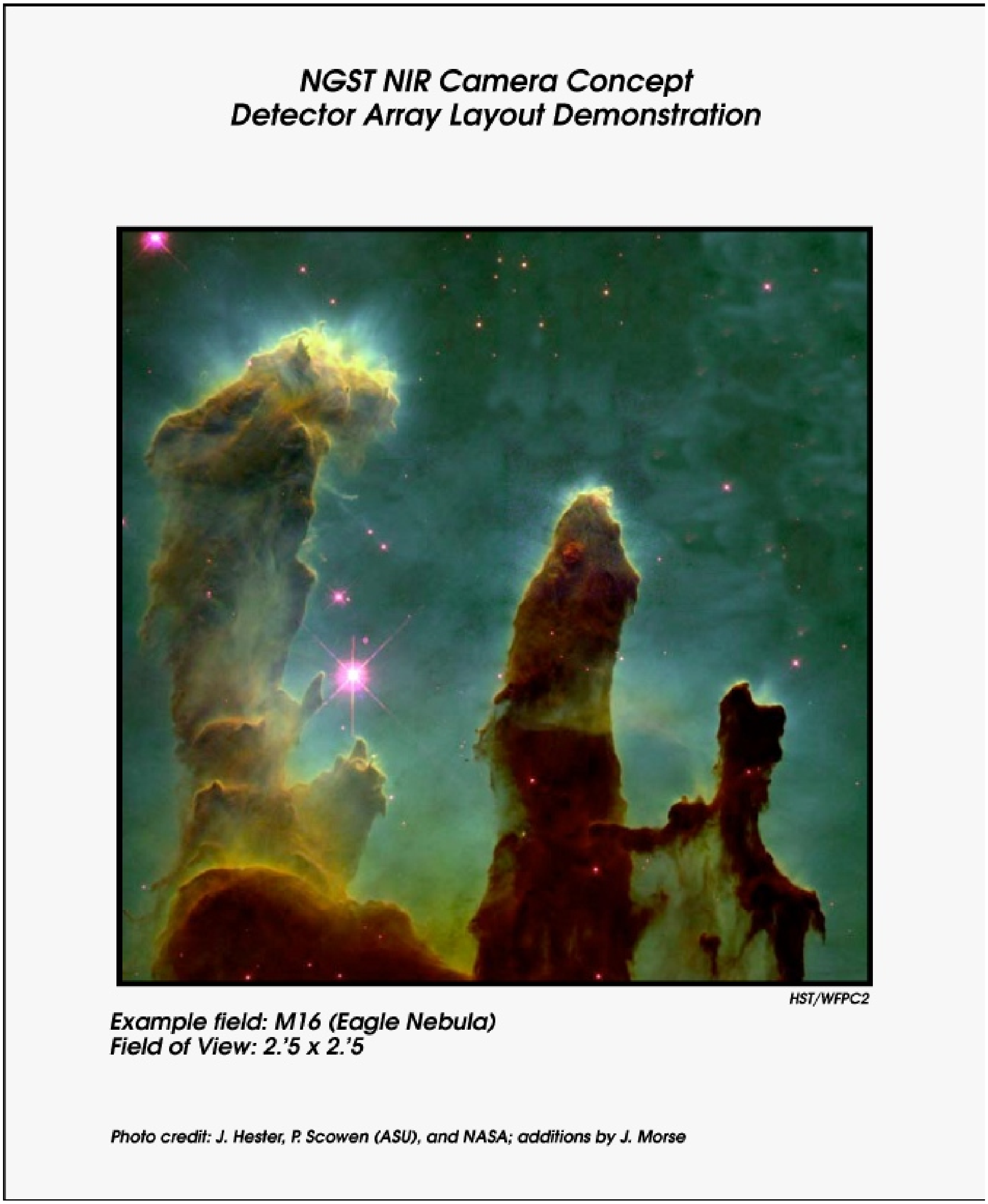

Fig. 5.— *The HST-WFPC2 image of M16 (with fake additions to the upper right-corner). This provides a familiar field of view to project the detector mosaic footprints.*

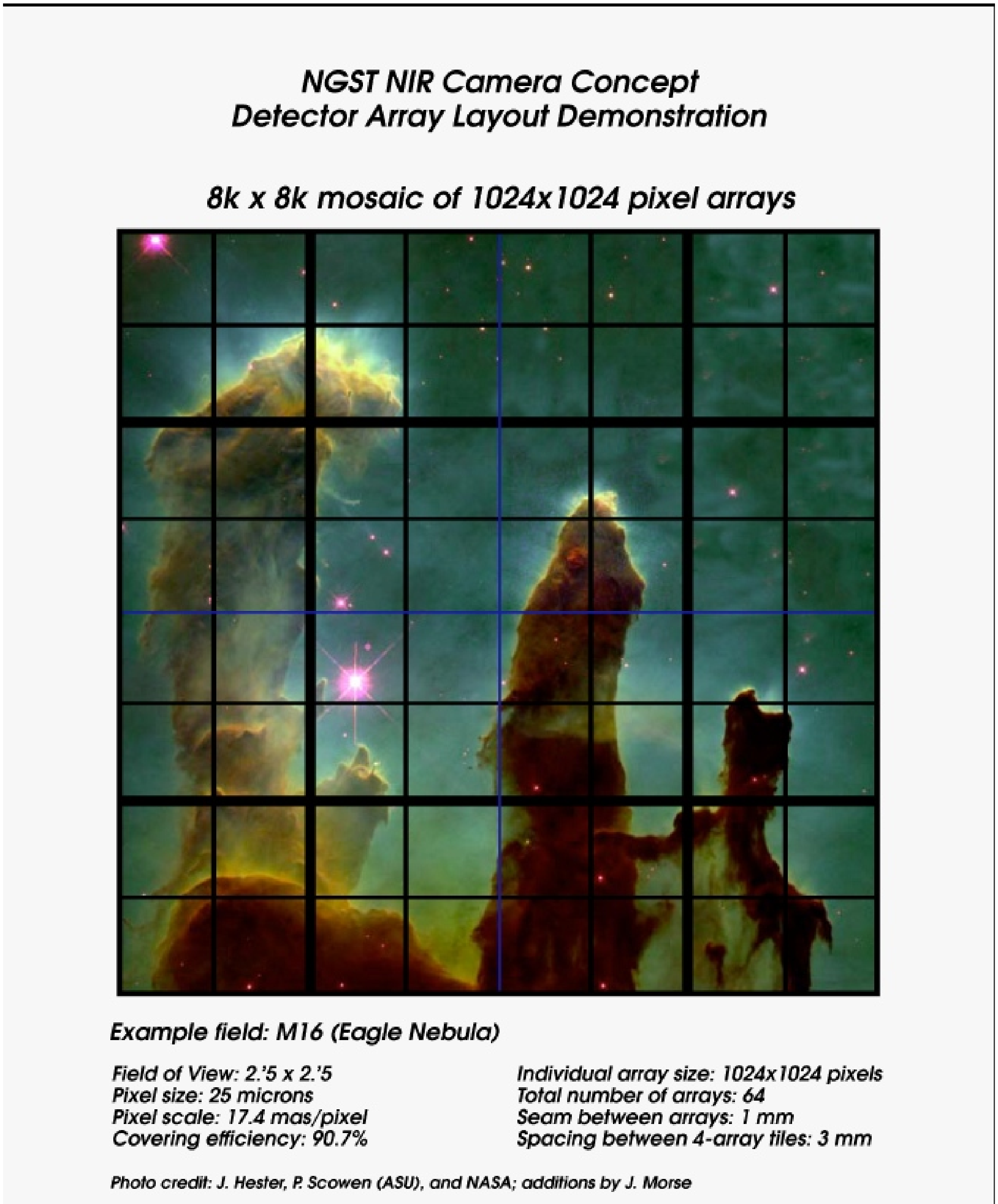

Fig. 6.— *The HST image of M16 as it would appear on a single exposure obtained with the 8192×8192 pixel camera populated with 64 1k^2 FPAs.*

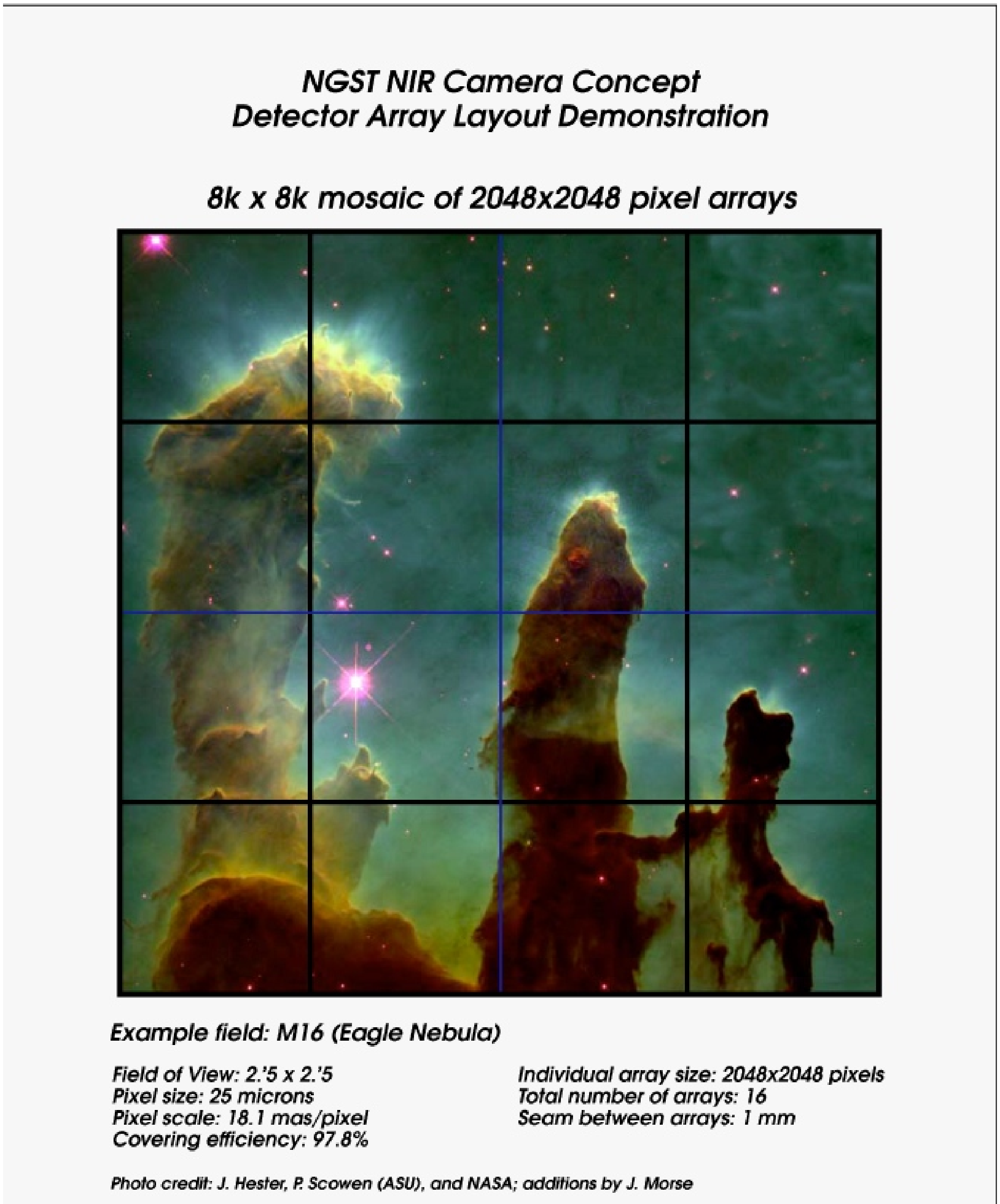

Fig. 7.— *The HST image of M16 as it would appear on a single exposure obtained with the 8192×8192 pixel camera populated with 16 $2k^2$ FPAs.*

developments. Raytheon is willing to take their time-proven ground-based astronomy designs and extend them to the 2k×2k format. In this case 27 μm pixels would be used. While not optimal for NGST, these ROICs would serve the purpose of making first article 2k×2k SCAs. This is very important as the production of large-scale FPA, HgCdTe included, has yet to be developed. With NGST in mind, fabricating 2k×2k SCAs with either the STAR or ALLADIN chips will provide a production cost yield exercise, perhaps better experienced earlier, rather than later.

Regardless of the approach to getting to a final version of the 2k×2k ROIC, the path to 2k×2k InSb on 25 μm (or smaller) pixel centers has already been established. Johnson-Mathey Electronics has been spending internal development funds to produce InSb wafers of a size large enough with which to fabricate 2k×2k (25 μm) detector. Work to ensure uniform electro-optical performance across the entire wafer will be needed, but for the short term, large wafers in quantities and of sufficient quality for the first lot of 2k×2k SCAs can be made available as needed.

To pull the 2k×2k InSb effort together, Raytheon is ready and willing to do the ROIC design, fabrication, and InSb hybridization together. For its part, Ball Aerospace is prepared to design and package the 2k×2k FPA modules into 4k×4k subassemblies and integrate them into a technology demonstration instrument of CU-CASA's (Center for Astrophysics and Space Astronomy) design.

Ball Aerospace Corporation has obtained ROM cost and schedule estimates for the 2k×2k InSb technology/instrument demonstrator. The total cost of this development is about 2M$.

6.1. Plans for device characterization:

The proposed activity will produce valuable data on several levels. As this project would be the first to hybridize 2k×2k scale InSb on ROICs, it will generate process variables and yield data. This will help quantify the cost of production NGST FPAs. Raytheon will also perform basic EO performance characterization including QE and dark currents and their spatial uniformities.

Ball Aerospace will perform FPA characterization of parameters most important at the system integration/performance level. This will include such parameters as read noise, linearity, NEI, dynamic range and possibly MTF/crosstalk. Ball has an IR lab with test equipment needed for these measurements. It includes a complete computerized test system designed for low-noise FPAs. The system has the capability to capture data and perform statistical analysis and image processing.

Ball has recently invested in a low-background, low-temperature test chamber for FPAs.

It was designed with the cold surface area and cold-shrouded volume for tested large-scale FPA assemblies. It is large enough to install and test NGST-style 4k$\times$4k FPA assemblies down to LHe temperatures. The proposed effort will provide a fully characterized detector assembly the instrument for integration and field-testing.

Ball is teaming with the Center for Astrophysics and Space Astronomy at the University of Colorado in Boulder to develop a portable dewar and camera system suitable for use on a telescope with narrow band-filters or in spectrographic mode. We will be seeking funds to build this proto-type camera/spectrometer through other NASA and NSF opportunities. Co-investigator Jon Morse has been discussing partnering with the Center for Astrophysics group on this camera project to secure engineering test and observing time on the new 6.5 meter MMT telescope being re-commissioned on Mt. Hopkins with a monolithic primary mirror.